Achieving low carbon emission using Smart Grid technologies

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***Abstract*—This paper presents a novel carbon emission flow (CEF) model to assess and analyze the carbon emission of each component in power networks. Through the use of information about CEF, demand side management (DSM) and supply side management (SSM) are combined to reduce the emission. Three levels of load curtailment and three strategies of renewable energy sources (RES) utilization are proposed. The IEEE 30-bus system is used to validate the framework of CEF, involving the UK actual daily data of electricity and RES. Simulation results confirm the feasibility of the proposed model and approaches. In the case of DSM, the higher penetration of DSM can result in a higher emission reduction. In the case of SSM, the proposed largest emission substitution strategy can achieve the best performance. And winter day shows a better carbon reduction than summer day in both cases.**

***Keywords*—Carbon emission flow, demand side management, power flow, renewable energy sources, supply side management, smart grid.**

I. Introduction

In order to curb the dangerous climate change, carbon emission reduction is imperative. The UK government is comitted to reduce the carbon emission by all kinds of ways, such as improving the energy efficiency, utilizing renewable sources, enhancing the fuel standard, investing low-carbon technologies and reducing the energy demand [1]. The UK Climate Change Act 2008 sets the carbon budgets and targets, which is a 80% reduction by 2050 compared with 1990 levels. The electricity supply takes an important place to achieve this target [2]. It accounts for around one third of the total emission in the UK for the past 15 years. The average carbon emission for electricity generation was 0.7 t/MWh in 1990, and decreased to 0.50 t/MWh in 2008. The anticipated aim is just 0.05 t/MWh by 2030 [3]. To achieve this goal, a comprehensive calculation system to assess and analyze the carbon emission for each component in power networks is necessary.

Existing research papers mainly focus on the carbon emission from the generation side. One basic method is to obtain the emission factors [4], [5]. These factors depend on the type of fossil fuel, and can be derived from historical data or experiments. Another method is to use life cycle assessment (LCA) [6], [7]. It can trace the whole life-time of carbon emission from raw materials to final combustion. Even though the majority of the carbon emission is produced at generation side, the electricity demand is the key that affects the supply. The understanding of the relationship between consumption and carbon emission is important. Carbon emission flow (CEF) model can virtually allocate the emission from generation side to customer side, specific to each component in the network [8], [9]. Based on this, the effectiveness of technologies that can be used for emission reduction in smart grid are more clearly. The renewable energy sources (RES) in supply side management (SSM) can benefit the reduction [11]–[13]. The quantity-based measures of RES support and energy mix strategy for carbon mitigation was studied in [11], [12]. And the policy about RES and carbon reduction was presented in [13]. The importance of demand side management (DSM) was also demonstrated in several aspects [14]–[16]. The energy conservation and carbon reduction performance in three kind of industries were examined in [14]. A method was proposed in [15] that use DSM to realize power reservation and encourage customers participating in carbon emission quotas. The involvements of electrical vehicle and demand response were considered in [16].

Compared with exisiting researches, the main contributions of this paper can be summarised as follows. First, the proposed system can offer accurate information of carbon emissions for each component in the network using CEF model. This enables a sensible measure to mitigate the carbon emissions according to components' specific information. Second, the UK actual daily data of electricity generation and demand is applied to the model. The time sensitivity and load curtailment sensitivity of DSM for carbon emission reduction can be precisely quantified. Finally, the utilization of RES in electricity generation is considered. Three different strategies in SSM are proposed for the emission reduction. The UK actual data is fed in to examine the feasibility and effectiveness of these strategies.

The rest of the paper is organized as follows. Section II gives an explanation of the proposed models, including the calculation model and system models. Section III presents three case studies and simulation results. Finally, Section IV concludes this paper.

II. Model Description

This section defines the four types of the CEF, and then explains how to calculate the CEF from power flow. The detailed mathematical derivation can be found in [9]. Three curtailment levels in DSM and three strategies in SSM are considered.

A. Calculation Model

The CEF is defined as a virtual network flow that describes the carbon emission flow form power network [9]. Suppose that the network consists of G generators, L loads and B buses. CEF rates and CEF intensity are specified first.

CEF rate: The CEF rate describes the amount of the CEF in the network per unit of time. The CEF rate R can be expressed as

$$R = \frac{dC}{dt} \tag{1}$$

in the unit of tCO_2/h, where C is the CEF flow, and t is the time index.

CEF intensity: The CEF intensity describes the amount of the CEF in the network per unit of active power. The CEF intensity i can be expressed as

$$i = \frac{C}{P} \tag{2}$$

in the unit of tCO_2/MWh, where P is the active power flow.

Four types of CEF are detailed as follows.

1) Ejected CEF (ECEF): The ECEF is the carbon emission outflow produced from generators to branches because of the combustion of fossil fuel. It can be analogous to the power generation in the power flow. The intensity of ECEF is determined by the types of generators and can be obtained directly. The ECEF rate can be calculated as

$$R_G = P_G \cdot I_G \tag{3}$$

where R_G is a B dimensional column vector of ECEF rate, I_G is a G dimensional column vector of ECEF intensity composed by i , and P_G is a $B \times G$ power flow distribution matrix.

2) Branch CEF (BCEF): The BCEF is the CEF through branches. It can be analogous to the power transmission in the power flow. The BCEF intensity is related to the branch active power outflow and node active power inflow. It can be calculated as

$$I_N = (P_N - {P_B^1}^T)^{-1} \cdot R_G \tag{4}$$

where I_N is a B dimensional column vector of BCEF rate, P_N is a $B \times B$ node active power inflow diagonal matrix, and P_B^1 is a $B \times B$ branch active power outflow distribution matrix. The BCEF rate can be calculated on the basis of the BCEF rate as

$$R_B = diag(I_N) \cdot P_B^1 \tag{5}$$

where R_B is a $B \times B$ BCEF rate matrix.

3) Injected CEF (ICEF): The ICEF is the carbon emission inflow obtained from branches to loads. It can be analogous to the power consumption in the power flow. The ICEF intensity has the same value as the BCEF intensity, and can be used to calculate ICEF rate. It can be expressed as

$$R_L = diag(I_N) \cdot P_L \tag{6}$$

where R_L is a $B \times L$ ICEF rate matrix, and P_L is a $B \times L$ load power distribution matrix.

4) Branch carbon emission loss (BCEL): The BCEL is the carbon emission caused by the power offset because of the transmission loss. It can be analogous to the branch loss in the power flow. The ICEF intensity also has the same value as the BCEF intensity, and can be used to calculate BCEL rate. It can be expressed as

$$R_I = diag(I_N) \cdot (P_B^0 - P_B^1) \tag{7}$$

where R_I is a $B \times B$ ICEL rate matrix, and P_B^0 is a $B \times B$ branch active power inflow distribution matrix.

Analogous to the power conservation, the CEF also conserves and can be expressed as

$$\sum_{i \in G} ECEF_i = \sum_{i \in B, j \in L} ICEF_{i,j} + \sum_{i,j \in B} ICEL_{i,j} \tag{8}$$

B. System Model

1) DSM: Smart grid technologies allow customers for a two-way flow of communication. Customers are able to participate in grid operations pertaining to power demand and generation. This brings the possibility for the demand reduction, especially at peak time. The peak demand always present a challenge to the sufficiency and security of supply. Because of the demand reduction, the corresponding carbon emission can be consequently mitigated. Three levels of load curtailments, 5%, 10% and 20% are proposed at each hour of the day for theoretical investigations.

2) SSM: SSM mainly focuses on the process of generation. The general emission-based order for power generation is coal-fired, oil, open cycle gas turbine, combined cycle gas turbine, nuclear, and renewable [17].

Therefore, RES are regarded as a clean and economic substitution for the conventional sources. By applying RES substitution in SSM, the carbon emission can be efficiently mitigated. While power generation is reduced at conventional generators by using various strategies, the associated reductions are compensated by the use of RES. Three strategies are proposed here for theoretical investigations.

- S1: Proportional substitution. All generators are assumed to have a same percentage of the generation reduction.
- S2: Largest generation substitution. Generators with largest generation amount are selected in order to have a generation reduction.
- S3: Largest emission substitution. Generators with largest emission amount are selected in order to have a generation reduction.

III. Case Study

An IEEE 30-bus system is used to validate the proposed model. It consists of 6 generator, 21 loads, 30 buses and 41 branches. One steady case and two real-time cases are presented.

A. Steady Case

In the steady case, the default power flow data from MATPOWER is applied to testify the calculation model and analyze the four types of CEF.

During one hour, the total ECEF of 6 generators is 360.67 tCO_2, the total ICEF of 21 loads is 356.05 tCO_2 and the total BCEL of 41 branches is 4.61 tCO_2, which satisfies the principle described in (8).

TABLE I
RESULTS OF ECEF CALCULATION FOR GENERATORS

Generators	Capacity [MW]	ECEF intensity [tCO_2/MWh]	ECEF rate [tCO_2/h]
G1	26.077	1.150	29.989
G2	60.970	1.350	82.310
G3	21.590	1.980	42.748
G4	26.910	2.480	66.737
G5	19.200	2.570	49.344
G6	37.000	2.420	89.540

The ECEF rates and intensities are listed in the Table I. The ECEF intensities are known based on the generators type. By working out the generation capacities for each generators, the corresponding ECEF rate can be calculated according to (1).

On the basis of the ECEF rate and power flow data, the remaining CEF rates and intensities can be obtained accordingly. The IEEE 30-bus system model is shown in Fig. 1. The BCEF rates between each bus are marked to illustrate the CEF distribution.

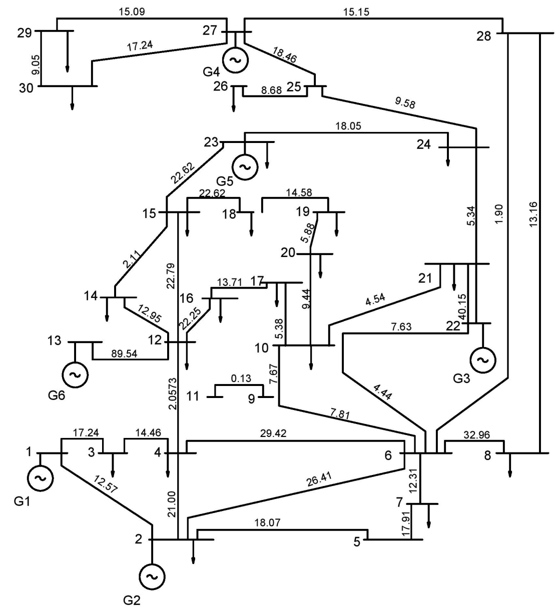

Fig. 1. The CEF model of IEEE 30-Bus system.

TABLE II
RESULTS OF ICEF CALCULATION FOR BUSES

Nodes	ICEF intensity [tCO_2/MWh]	ICEF rate [tCO_2/h]
Bus 21	2.030	35.5179
Bus 22	2.030	0.000
Bus 23	2.570	8.2246
Bus 24	2.538	22.0812

The ICEF rates and intensities from bus 21 to bus 24 are selected in Table II. For bus 21, the only inflow power comes from bus 22; therefore, it has the same ICEF intensity as bus 22. For bus 22, the inflow power comes from G3 and bus 24. The ICEF intensity of bus 22 is a little bit lower than bus 23 because G3 has a relatively low intensity. If the inflow power comes from G3 reduces, the ICEF intensity of bus 22 will increases but cannot be higher than bus 23. The ICEF rates of bus 22 is 0, because there is no load connected to it.

B. DSM case

In the DSM case, the UK actual daily power generation and demand from the Grid Watch are fed into the IEEE 30-bus system. These data cover an entire day with 24 time slots. The CEF results in this section enable the analysis of practical implementation and comparison with load curtailment scenarios.

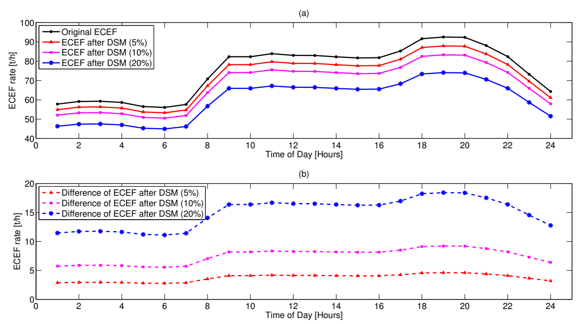

Fig. 2. (a) Daily ECEF with respect to various degrees of DSM on January 14, 2016; (b) Difference of daily ECEF with respect to various degrees of DSM on January 14, 2016.

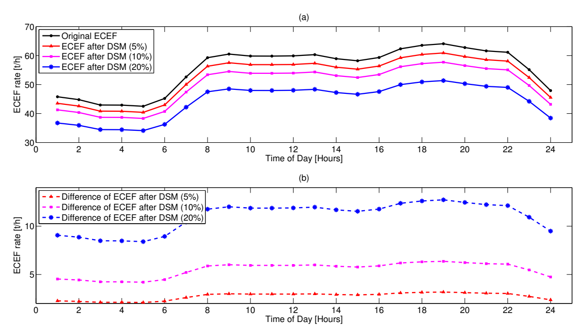

Fig. 3. (a) Daily ECEF with respect to various degrees of DSM on July 14, 2016; (b) Difference of daily ECEF with respect to various degrees of DSM on July 14, 2016.

Fig. 2 and 3 show the daily ECEF with various degrees of DSM on Jan. 14th (typical winter day) and Jul. 14th (typical summer day) in the UK, respectively. The ECEF pattern has a similar trend as electricity demand. There is a peak emission period from 6 pm to 10 pm, and a valley emission period from 12 am to 6 am. It is clearly that during both days, as the penetration of DSM increases, the ECEF decreases.

Compared to the selected two days, the DSM has a better level of performance in whole day on Jun. 14th than on Jul. 14th, and the emission reduction during the peak period is also more significant on Jan. 14th than on Jul. 14. These results are representative for summer season and winter season. First, generally, the electricity demand is higher on winter days than summer days, 36% higher on average [18]. Therefore, with the same penetration of DSM, the electricity demand would reduce more on winter days, subsequently influencing the ECEF. Second, the peak demand on summer days is much lower than winter days. This is because more lighting and heating are needed for winter days during the night. As such, the DSM could have a larger effect during the peak time on winter days.

C. SSM case

In SSM case, the UK actual RES power data from Grid Watch are applied in the IEEE 30-bus system. The UK's RES are primarily dominated by wind, solar and hydro. And the utilization of wind energy and solar energy has a significant increase these years [19]. These sources have a tiny carbon emission intensity, 0.034 tCO_2/MWh for wind energy and 0.040 tCO_2/MWh for solar energy [20]. Their deployment enables ECEF intensities to decrease, therefore influence other CEF intensities and rates.

For strategy S1, all generators experience a same percentage of generation reduction, which can be compensated from RES instead of conventional sources.

For strategy S2, generators are listed in descending order of generation capacity: G2, G6, G4, G1, G3 and G5. G1 has the largest generation capacity in the system; therefore, RES can be used to substitute only part of its generation from the conventional method.

For strategy S3, generators are listed in descending order of ECEF intensity: G5, G4, G6, G3, G2 and G1. G5 has the largest ECEF intensity, but the smallest generation capacity. During some time period, RES can contribute part of its generation. While during some time period, when RES are sufficient, G5 can be shut down and part of G4's generation can come from RES.

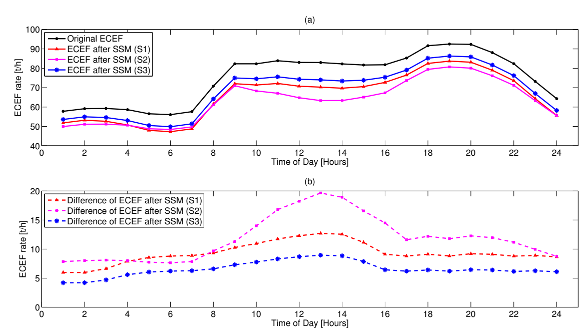

Fig. 4. (a) Daily ECEF with respect to various degrees of SSM on January 14, 2016; (b) Difference of daily ECEF with respect to various degrees of SSM on January 14, 2016.

Fig. 4 and 5 show the daily ECEF with SSM on Jan. 14th (typical winter day) and Jul. 14th (typical summer day) in the UK, respectively. For both days, the emission reduction varies over time because RES has the inherent intermittent characteristic. Among three strategies, S3 has the best performance, then S1 and S2. It makes sense because S2 is a relatively moderate strategy, while S3 gives priority to the emission intensity and S2 gives priority to the generation capacity.

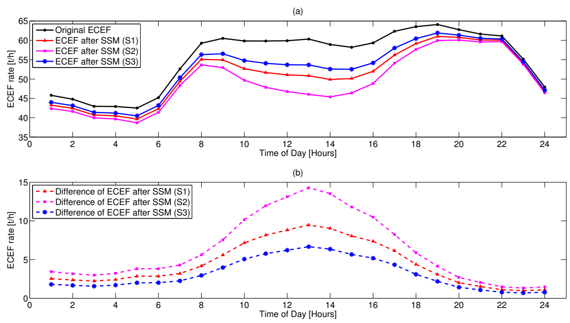

Fig. 5. (a) Daily ECEF with respect to various degrees of SSM on July 14, 2016; (b) Difference of daily ECEF with respect to various degrees of SSM on July 14, 2016.

Compared to the selected two days, the SSM also has a better level of performance on Jan. 14th than on Jul. 14th. These results are representative for winter season and summer season. Among all the RES used for electricity generation, wind energy has the largest share of 49.8%, while solar energy has a share of 5.8% [19]. The wind speed during winter season and summer season is 9.7 knots and 7.8 knots, respectively, on average from 2002 to 2011 [21]. Even though winter days have less solar energy because of the shorter sunshine duration, they still have more RES available because of the faster wind speed. Therefore, winter days are able to have a better emission reduction than summer days.

IV. Conclusion

This paper used a CEF model to calculate carbon emissions derived from power flow. Two concepts, carbon emission intensity and rate, and four CEF types, ECEF, BCEF, BCEL, and ICEF are proposed. This model can accurately quantify and assess the carbon emissions for each component in the network. The IEEE 30-bus system with default data is applied to illustrate the framework of this model. Furthermore, to demonstrate the practical use of CEF model, the UK actual daily data about RES, and demand and supply in typical winter day and summer day are applied. Three levels of load curtailment in DSM and three strategies in SSM are proposed for the purpose of emission reduction. In the DSM case, the emission reduction has the similar trend as the electricity demand. With the increasing penetration of DSM, the emission reduction increases accordingly. In the SSM case, the emission reduction fluctuates over time because the uncertainty of RES. Largest emission substitution strategy has the best performance, and proportional substitution strategy takes second place, then largest generation substitution strategy at last. In both cases, winter day provides a better carbon reduction than summer day.

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